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FIBER OPTICS-MAJOR COMMUNICATIONS BREAKTHROUGH.(U)

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TECHNICAL NOTE NO. 9-78

FIBER OPTICS - MAJOR COMMUNICATIONS BREAKTHROUGH

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EMP	Light Propagation	Photodiodes
Fiber Optics	Lightwave Communications	Wideband Communications

20. ABSTRACT (Continue on reverse side if necessary and identify by block number)

This TN is a basic tutorial on the relatively new art of fiber optics communications. A brief history is included along with a general discussion of fiber optics fundamentals and the surrounding theory. System components are presented with current performance data and cost factors, and comparisons with metallic path parameters are made. Typical systems employment, potential DCS applications, and existing problem areas are also discussed.

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JULY 1978

Prepared by:

- Roy B. Shrout, Jr.

Approved for Publication:

E. D. Frankhouser

E. D. FRANKHOUSER
Colonel, USA
Director

FOREWORD

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Director
Defense Communications Engineering Center
1860 Wiehle Avenue
Reston, Virginia 22090

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I. INTRODUCTION

Terrestrial communications systems, in their most fundamental form, may be separated into two categories: one in which there is a physical path or connection between transmitter and receiver; and a second category in which no physical connection is present.

In the latter classification are radio systems of all frequency ranges and propagation modes - including line-of-sight, troposcatter, ionospheric reflection, and terrestrial repeater - as well as various types of optical systems which involve light transmission across open space. All of these terrestrial systems have a degree of flexibility in that, with no physical connection required between transmitter and receiver, there is no requirement to own, lease, or control the real estate between terminals.

However, because their propagation paths traverse open space, these systems are to a degree dependent on the presence of certain atmospheric phenomena, and/or on the absence of others, to achieve reliable communications. Further, those transmission paths are subject to easy interception, jamming, path blockage, and other man-generated problems.

In contrast, once the necessary right of way has been acquired between transmitter and receiver for a physical link (traditionally metallic) many of the above mentioned difficulties can be overcome. When properly installed, the physical path systems are not susceptible to the variations in quality and reliability which often plague open path systems.

Unfortunately, this does not mean that physical path systems are without problems. In fact, a substantial number of negative factors do impact physical metallic links. These include bandwidth limitations, radio-frequency interference (RFI), electromagnetic interference (EMI), lightning effects, physical size and weight constraints, moisture, corrosion, and crosstalk.

Thus, throughout most of the history of electrical communications, it is fact that many of the open path communications link problems which were "solved" by turning to a physically connected metallic path, were not really "solved" at all - they were simply traded-in for a different set of equally bothersome problems.

What has been needed since the advent of wireline communications is a physically connected link which (by its nature) eliminates the problems inherent to open path systems, but which also overcomes the numerous difficulties associated with metallic wirelines and cables.

The solution, Fiber Optics, has arrived!

This technical note includes some background on light and light communications, followed by a general discussion of fiber optics fundamentals and theory. Also covered are the system components, performance data, and cost factors, as well as detailed comparisons with metallic path parameters. The relative advantages of utilizing fiber optics in a pair of typical communications systems; some potential DCS applications; and the few problems remaining in this new approach to communications, are also discussed.

II. BACKGROUND

1. LIGHT

"The radiation, in a small region of the electro-magnetic spectrum, produced by the transitions of electrons from states of higher energy to states of lower energy traveling in a vacuum at 186,281 miles per second, in basically a straight line from source to detector."

The first recorded use of light for operational communications took place well before the birth of Christ with the Greek Army's employment of signaling mirrors. Other more notable historical examples include the English bonfires in 1588 which warned of the approach of the Spanish Armada, and Paul Revere's lantern signals in 1775. During the late 1800's Heliographs were used by the U.S. Army in the southwest, and even today the U.S. Navy makes use of signal lights to communicate between ships at sea.

On the theoretical side, as far back as the early 1600's, Galileo Galilei was learning to manage the optical transmission character of light. Nearly 100 years later, in 1704, Sir Isaac Newton's nature of light and wave phenomena experiments were published. In the early 19th century, A. J. Fresnel established the initial mathmatical basis for light transmission, and about 40 years later James C. Maxwell developed his light propagation equations. In 1902 Max Planck demonstrated that light energy is inversely proportional to wavelength, and was followed by Albert Einstein's unifying theory which provides the concept of light as we know it today.

2. FIBER OPTICS

The first use of the term "fiber optics" for communications is generally attributed to an Indian physicist, Dr. Narinder S. Kapany, while working on his PhD at the Imperial College of Science and Technology in London in 1954. Dr. Kapany defined fiber optics as:

> "The art of the active and passive guidance of light (rays and waveguide modes) in the ultraviolet, visible, and infrared regions of the spectrum, along transparent fibers through predetermined paths."

Unfortunately, until just a few years ago the definition was really all that existed. The advancement of this new "art" came recently and rapidly as a result of several key technology breakthroughs. H. Maiman's demonstration of the Ruby laser in 1960, followed just 2 years later by the simultaneous successful development of semiconductor junction lasers by General Electric, IBM, and MIT (Lincoln Lab), provided the powerful, coherent light sources which would be needed for practical light communications.

After experiments were conducted using 1-centimeter diameter gas-filled light pipes in the mid-60's, K. C. Kao, in 1968, became the first communications expert to direct serious attention to glass fibers for long distance communications.

At that time typical fiber losses were above 1,000 dB/km, but Kao suggested that glass materials of greater purity could significantly reduce losses. Soon British, Japanese, German, and American efforts were underway, and the real breakthrough came in 1970 when the Corning Glass Company first achieved (in the laboratory) several hundred meters of a 20 dB/km fiber. This was of a sufficiently low loss to make fiber optics communications practical.

During the succeeding years, refinements in theory, and dramatic improvements in the design and production techniques for fibers, photo diodes, injection lasers, and light emitting diodes, have resulted in the present readiness of fiber optics to make its formal debut as the new standard for the world of communications.

III. THE FIBER OPTICS COMMUNICATIONS SYSTEM

Fiber optics is the generic title now almost universally applied to the technique of creating a communications transmission system by modulating a fairly coherent light source, passing that light through a clear optical solid conductor, and receiving the light at the distant end for conversion back to the original modulating signal.

Thus, in its most elementary form, a fiber optics link consists of just three components: An optical driver (the light source), a light conductor, and an optical (light) detector.

The fiber optics link is usually employed to provide the transmission path between communications-electronics (C-E) equipment at two locations, as shown in Figure 1.

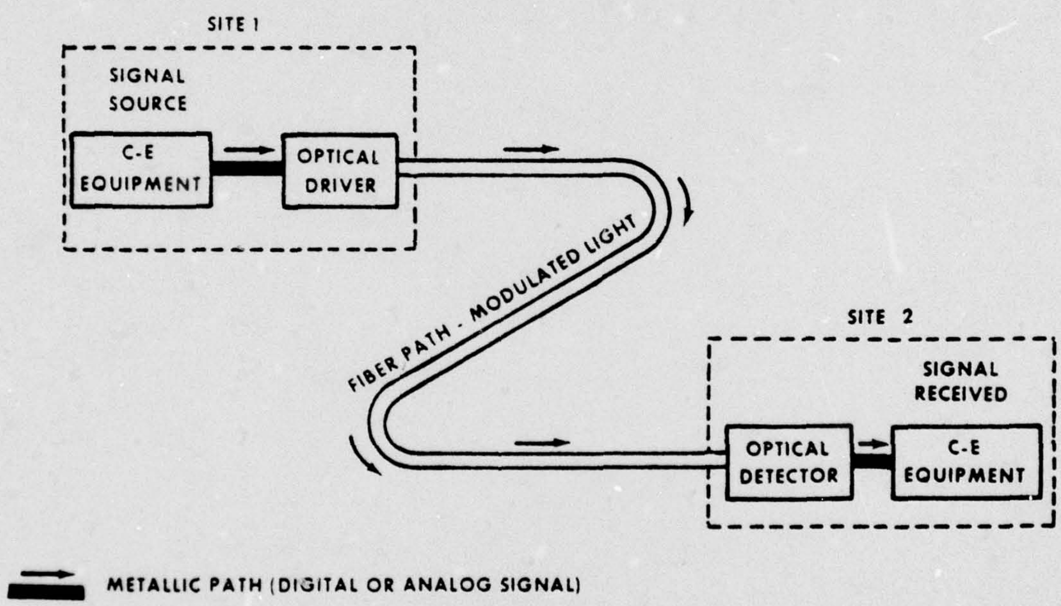


FIGURE 1. BASIC FIBER OPTICS LINK

1. OPTICAL FIBERS

There are two basic methods of employing optical fibers to achieve an effective light bearing path: single fiber, and fiber bundle. Both approaches are illustrated in Figure 2.

In the center of Figure 2 is shown a single glass fiber. Each fiber is individually drawn from high quality glass (or occasionally

plastic) and is on the order of 100 microns in diameter for most applications.

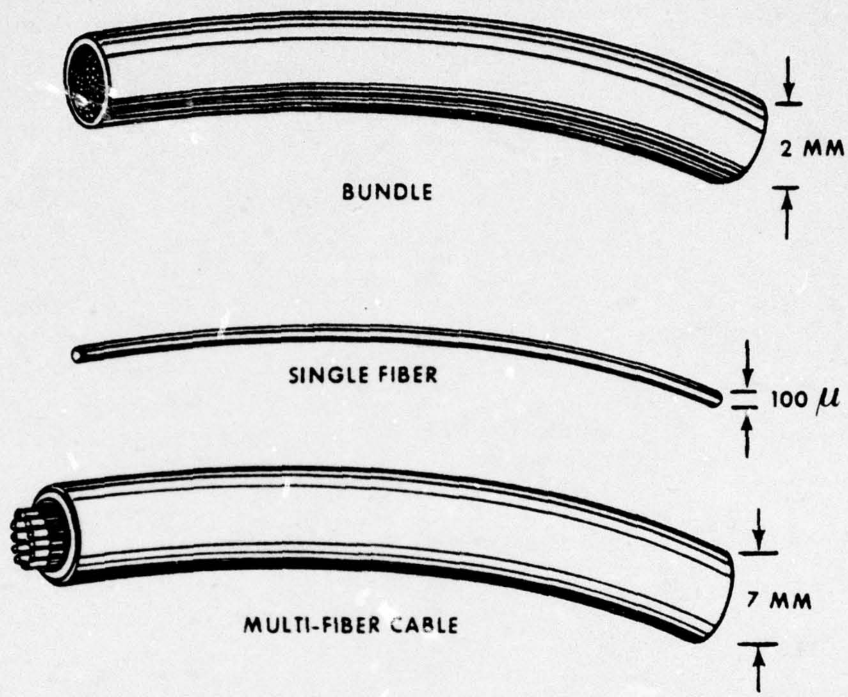


FIGURE 2. FIBER OPTICS TRANSMISSION PATHS

In the early days of fiber optics technology, when only high loss, easily broken fibers were available, it was usually necessary to use the bundle technique to assure a satisfactory transmission path. Several hundred fibers are held together and then surrounded by a protective sheathing to form a bundle type cable, shown in the upper part of Figure 2.

In application, the modulated light is applied across all of the fibers in the bundle so that even with high individual fiber attenuation and internal fiber breakage, a usable percentage of the light, bearing the message, will get through to the detector. In other words, in the bundle technique each of the several hundred fibers in the cable is carrying the same message.

The bundle technique is still of practical value today for specific applications, particularly when an extra reserve of strength or redundancy is required such as on military aircraft or combat vessels.

As low loss, high strength fibers were developed, along with techniques to connect and/or splice on the small scale required, the single fiber approach became practical and dominant. Each single fiber is carefully manufactured and sheathed with protective material to form an individual circuit path. Usually two or more single fibers, each wrapped and protected, are formed into a multifiber cable as shown at the bottom of Figure 2. That typical cable, which is also shown in end view in Figure 3, consists of 10 single fibers, each individually jacketed, and then formed into a cable roughly 7mm (one quarter inch) in diameter, with tensile strength members and external protective sheathing.

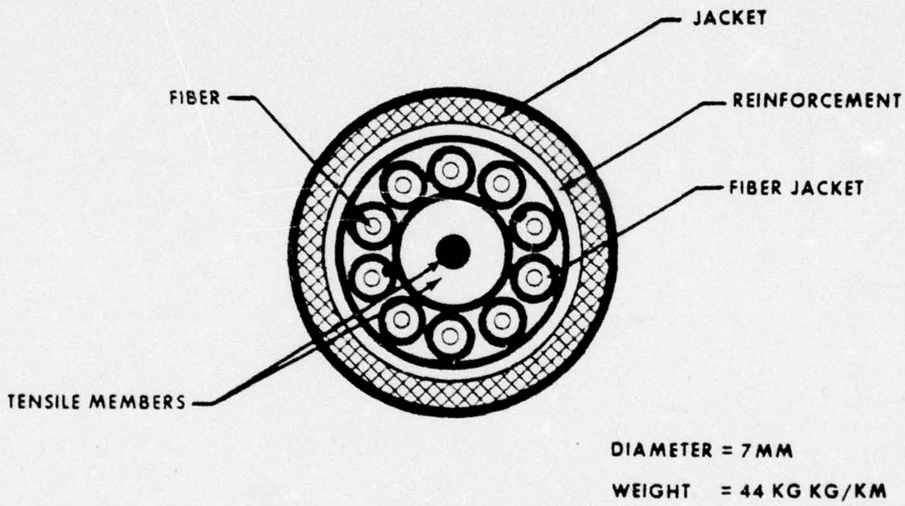


FIGURE 3. FIBER OPTICS 10-FIBER CABLE

Typical fiber optics cables made today use polyurethane as a buffer material to protect the individual fiber, DuPont KEVLAR® for tensile strength members, and polyurethane and/or polyvinyl chloride (PVC) for jacketing and sheathing.

The 10-fiber cable shown in Figure 3 can thus provide 10 independent high capacity communications channels, although in practice only seven or eight of the fibers would be activated, leaving two or three spare fibers available for expansion or emergency.

As previously mentioned, as recently as 10 years ago fiber optics was completely impractical as a communications medium due to the very high attenuation (1,000 dB/km) of existing fibers. Today, quality fibers with only 5 to 10 dB/km attenuation are available on the open market, and fibers on the order of 1 dB/km attentuation have been produced in the laboratory.

As a means of emphasizing the progress, if sea water were as pure and transparent as today's glass fibers, from the ocean's surface you could clearly view the ocean's floor at its deepest point.

In fact, the attenuation losses in commercial fibers have now been reduced to the point where, in planning wideband systems, the spacing of repeaters is no longer based on a fiber attenuation loss budget, but on one or more types of group-delay distortion. This "new" problem is discussed in some detail in the section on theory.

There is an important relationship between the wavelength of the light being transmitted and the attenuation rate of the glass fiber. Figure 4, on the following page, is a typical optical fiber attenuation chart for a low loss glass. The broad, high attenuation band at $\lambda = 0.95$ microns is due to OH ion absorbtion. Material scattering centers, small compared to λ, are frozen into the glass as it solidifies, and cause Rayleigh scattering loss, which varies as $1/\lambda^4$ as shown. But of primary interest to fiber optics systems designers are the two low loss spectral regions:

$\lambda = 0.8$ to 0.85 microns, and $\lambda = 1.06$ microns

Little thought was required to recognize that with the glass attenuation profile essentially fixed, the achievement of a successful fiber optics system would depend on just two factors: developing reasonably powerful optical sources to operate in either (or both) of the low loss regions; and developing photo detectors with good sensitivity to receive at those same wavelengths.

As it worked out, with proper selection of material, there were no major obstacles to accomplishing both objectives.

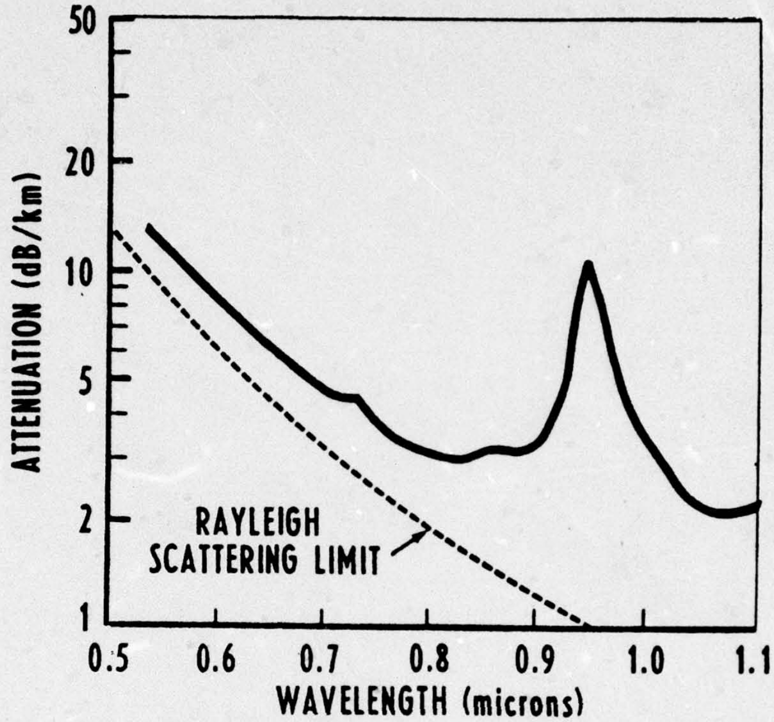


FIGURE 4. TYPICAL OPTICAL FIBER ATTENUATION CURVE

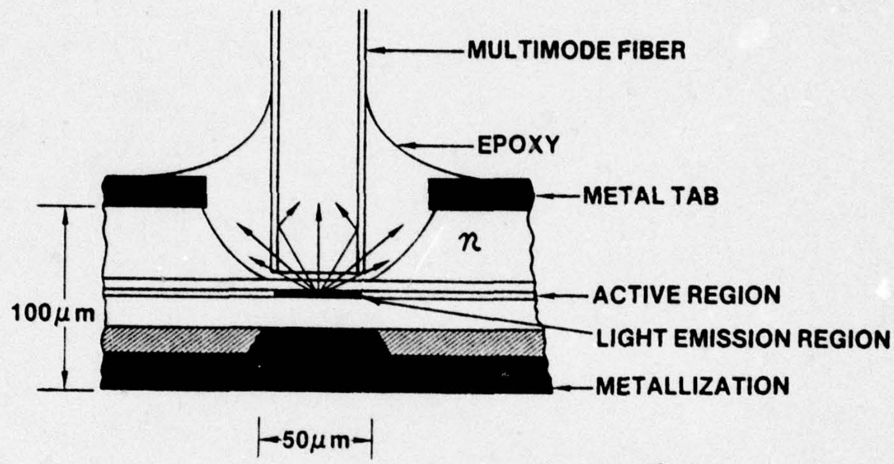
Note: The many valleys and peaks in the attenuation curve would seem to belie statements and another attenuation chart that appear later in the theory section. Those indicate that fiber attenuation is essentially "flat" across the digital spectrum of modulation bandwidth. Actually, both the diagram above and the one to follow are correct. For clarification it must be remembered that we are now far up in the electromagnetic spectrum with wavelengths measured in microns. Thus a modulation bandwidth of even 1,000 GHz would occupy only a small dot along the horizontal axis of Figure 4 above.

2. LIGHT SOURCES

There are two types of light source devices currently in service as optical drivers. One is the light emitting diode (LED) and the other is the injection laser. The "low budget" source is the LED. The fiber optics LED is a refined version (smaller and more powerful) of the LED units found in the visual displays of pocket calculators, digital clocks, and CB radios. Figure 5 shows the cross section of a Burrus LED. The Burrus LED (named for its inventor at Bell

laboratories) is characterized by the well which is etched in the top of the n region.

A second type of LED is the face emitting LED (which is similar in appearance to the injection laser shown in Figure 6). Both LED types have about the same radiance and are usually made with gallium arsenide with 10 percent aluminum doping to produce light at 0.8 microns, just inside one of the two low loss regions (Figure 4).



RADIANCE	=	10-100 W/sr/cm^2
P (FIBER)	$\simeq$	0.1 mW
MODULATION BANDWIDTH	=	200 MHz
SPECTRAL LINEWIDTH	=	350 Å
PROJECTED LIFETIME	>	100,000 HOURS

FIGURE 5. BURRUS LED

The fairly coherent light output of the LED has a spectral width on the order of 350 angstroms and can be successfully modulated to a few hundred MHz. Figure 5 also depicts the most common method of coupling the optical fiber to the LED. In production, a short length or "Pigtail" of fiber is positioned to establish the connection, and is then permanently fastened to the LED with epoxy. Later, in installing the system, it is only necessary to use connectors or a splice to join the other end of the "pigtail" with the outgoing fiber cable. Similar methods are used for coupling injection lasers and photo detectors to optical fibers.

The high efficiency, higher cost light source is the semiconductor injection laser, shown in Figure 6. This device employs a double-heterojunction structure, as illustrated in the

figure, to obtain better carrier and optical photon confinement for increased gain. The power output to the fiber is about 2.5 milliwatts, or 25 times that of an LED.

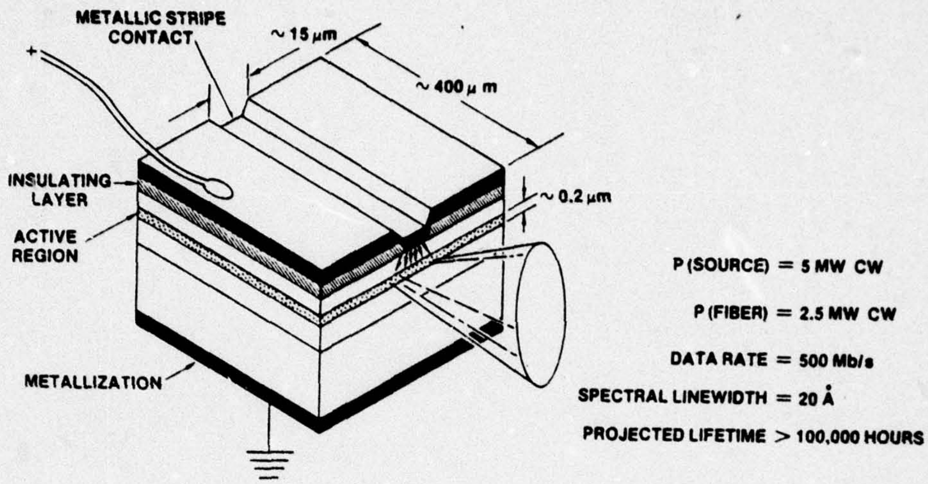


FIGURE 6. SEMICONDUCTOR INJECTION LASER

The laser spectral linewidth is narrow, on the order of 20 Angstroms, permitting modulation into the several GHz range. As with the LED, the furthest developed and most used material for injection laser production is gallium arsenide with aluminum doping to the 0.8 micron low loss region.

A substantial level of research is also being expended on an even more coherent light source, a solid-state ion laser made with a crystal of YAG (yttrium-aluminum-garnet) doped with neodymium (Nd). The output of an Nd:YAG laser is in the 1.06 micron low loss region and its longer wavelength provides an additional Rayleigh scattering advantage (see Figure 4). The spectral width is less than 1 Angstrom. With these parameters, modulation bandwidths of many gigahertz are possible. However, the Nd:YAG rods must be optically excited or "pumped" by external LED's, and due to a long fluorescence lifetime of the upper laser level, must be externally modulated as well. Thus the solidstate ion laser is complicated and costly and it appears that the semiconductor injection laser will remain the primary high quality light source for wideband fiber optics systems for some time.

3. LIGHT DETECTORS

Just as there are two primary types of light sources, there are two basic categories of light detectors.

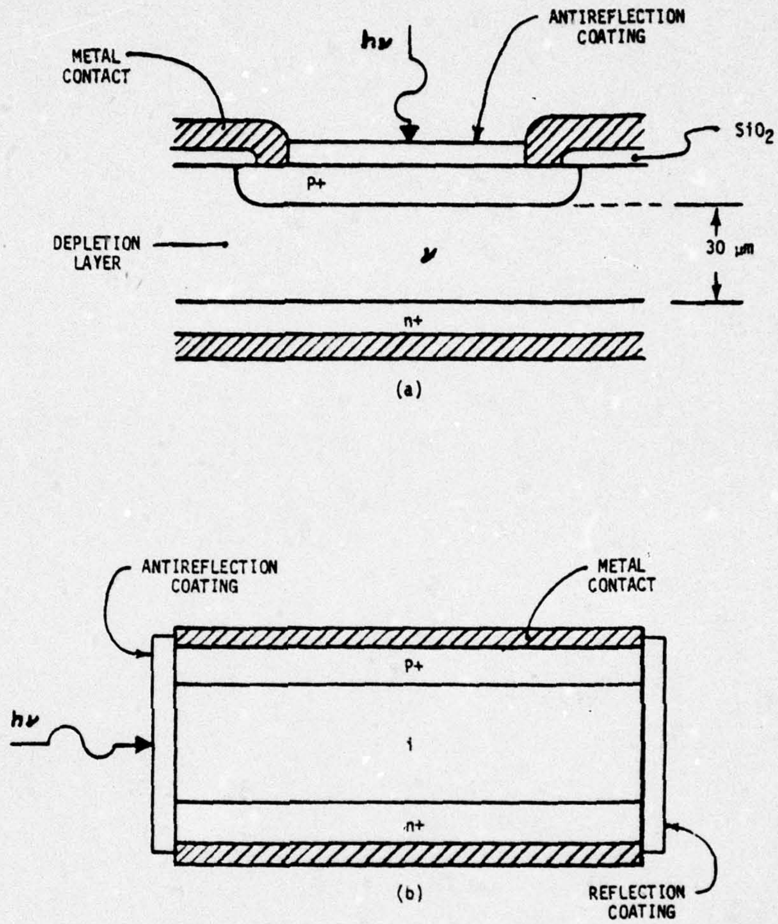


FIGURE 7. OPTICAL P-I-N DIODES

The "Low Budget" optical receiver is the junction type positive-intrinsic-negative (p-i-n) photodiode. Three commonly used semiconductor materials are available with responses in the 0.8 to 0.85 micron region: gallium arsenide, silicon, and germanium. The latter two materials are also responsive in the 1.06 micron region. The silicon technology is the most highly developed and it is therefore the preferred material for most diodes.

Figure 7 shows the construction details of two p-i-n diodes. Part (a) is a front-illuminated silicon photodiode and Part (b) is a similar side-illuminated device. For use at 0.8 microns the depletion layer would be about 30 microns thick, producing a quantum efficiency of 70 percent and modulation to several hundred MHz - an excellent match for the LED outputs discussed earlier.

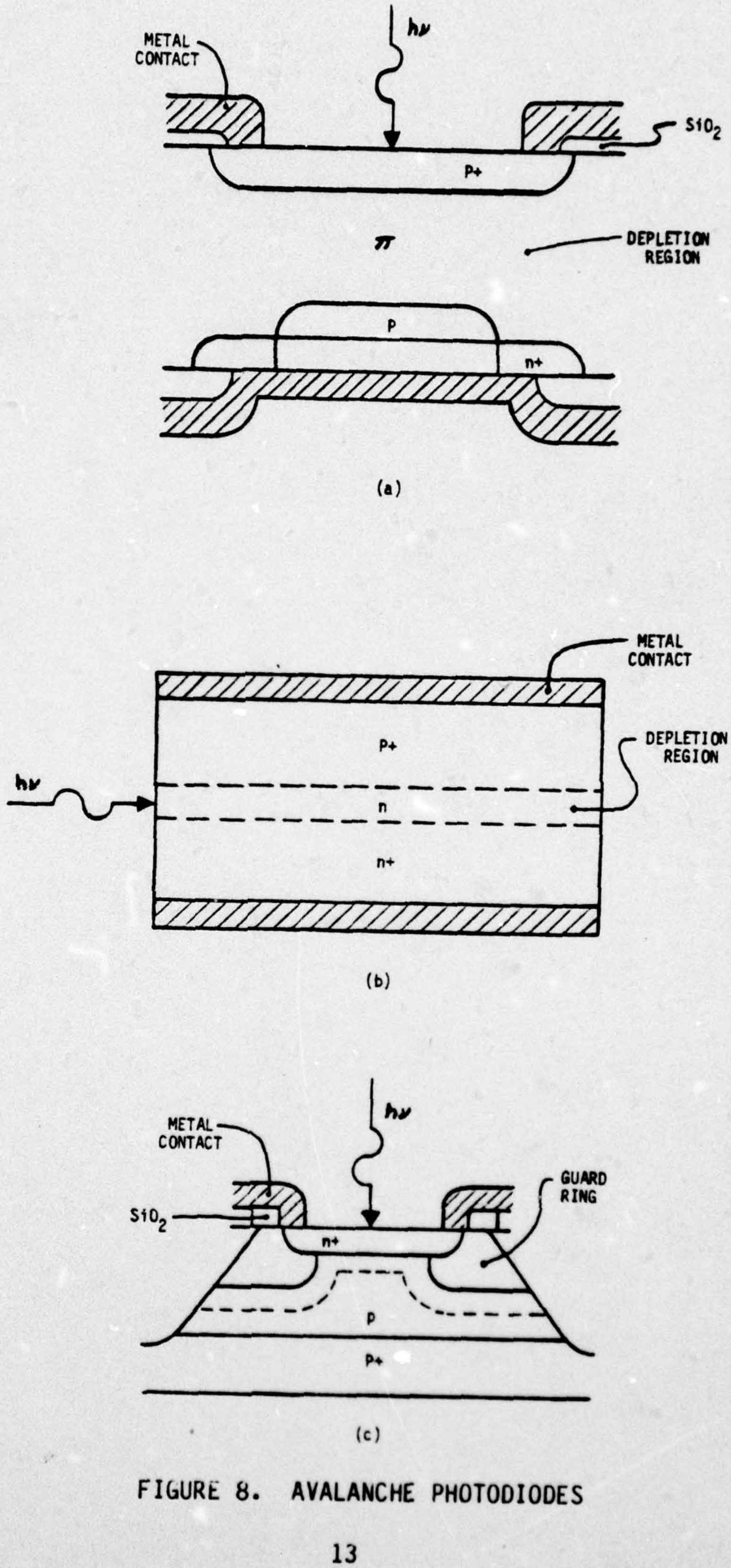


FIGURE 8. AVALANCHE PHOTODIODES

The high performance, high cost optical receiver is the avalanche photodiode (APD) which combines optical detection with internal amplification of the photo current. As with the p-i-n diode, silicon is the usual material, but high quality germanium APD's have also been produced. Gain times bandwidth (G x BW) products in the range 30 to 100 have been reported for both silicon and germanium APD's.

Figure 8 depicts three types of construction. Part (a) is a front-illuminated silicon APD. Part (b) is a side-illuminated silicon APD which has shown superior response at $\lambda = 1.06$ microns and is the most likely choice in that region. Part (c) is a front-illuminated APD of germanium construction.

Not only is the APD cost per unit still about three times that of a p-i-n photodiode, but the APD requires a power supply of several hundred volts gain-stabilized against variations in temperature. Thus APD use is generally restricted to higher cost systems in combination with lasers to achieve wide modulation bandwidths.

Thus, two systems configurations are available as listed in Table I.

TABLE I. COMPARISON OF LOW COST AND HIGH PERFORMANCE SYSTEMS

	Low Cost	High Performance
Optical Driver	LED	Injection Laser
Fiber	High loss or Bundle	Low loss
Fiber Attenuation	20 dB/km +	5 dB/km ±
Optical Detector	p-i-n diode	APD
Modulation Bandwidth	MHz - several Hundred	GHz -several
Spectral Width	350 Angstroms	20 Angstroms
Emission Wavelength	0.8 Microns	0.8 Microns
Repeater Spacing	2 km	8 km

IV. OPTICAL FIBER THEORY

The transmission of light down a cylindrical glass fiber waveguide is a very complex physical phenomenon which is most accurately, though with some difficulty, portrayed through the use of wave formalism. On the other hand the use of ray optics is not incorrect, and, if skew rays are avoided by taking a rectangular rather than circular cross section, a simpler, more easily understood explanation is the result.

1. STEP-INDEX MULTIMODE FIBER

The most elementary fiber optics waveguide consists of a glass fiber with a core 60 to 80 microns in diameter and an index of refraction n_1 surrounded by a 20 to 40 micron thickness of cladding (glass or plastic) with a somewhat lower index of refraction n_2. This type of fiber construction is called step-index multimode, as there is just a single sharp change, or step, in the refracting index (core to cladding), and the fiber core is large enough to accept light at many angles of incidence (multimode).

Figure 9 shows a typical meridional ray, R, entering a step-index, multimode fiber.

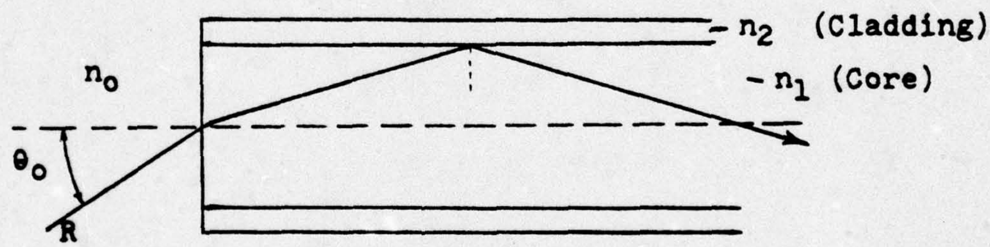


FIGURE 9. LIGHT RAY ENTERING A STEP-INDEX MULTIMODE FIBER

The maximum angle of light ray acceptance (maximum value for the external angle θ_o) where the ray R will still be totally internally reflected, is defined as θ_c. The exact value of θ_c is dependent on the indices of refraction of the core and cladding; in the following relationship:

$$\text{Sin } \theta_c = (n_1^2 - n_2^2)^{1/2}$$

In the traditional optic sense, the quantities in the above equation also define the numerical aperture (light accepting capacity) of the fiber. That is:

$$\text{NA} = \text{Sin } \theta_c$$

All light entering the waveguide at external angles θ_o equal to or less than θ_c will be internally reflected and transmitted. Light entering at angles greater than θ_c, will be partially refracted into the cladding and quickly dispersed, as shown in Figure 10.

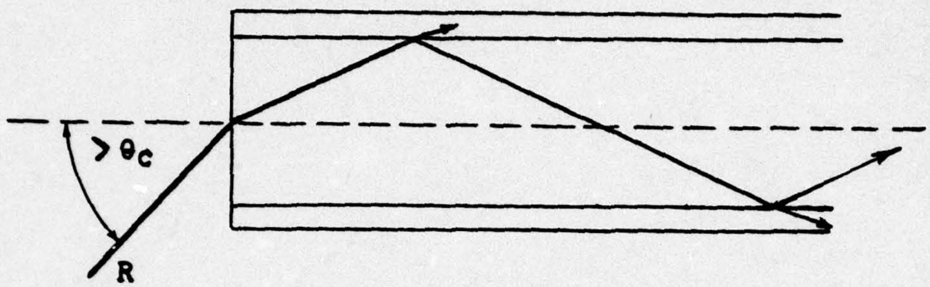


Figure 10. DISSIPATION OF LIGHT RAY ENTERING A FIBER AT AN ANGLE GREATER THAN θ_c

As the light rays travel down the length of the glass, they are attenuated (as would be expected) by material absorbtion due to impurities in the glass.

Figure 11, on the following page, compares the characteristic attenuation of two typical high-grade optical fibers with that of several commercial metallic coaxial cables.

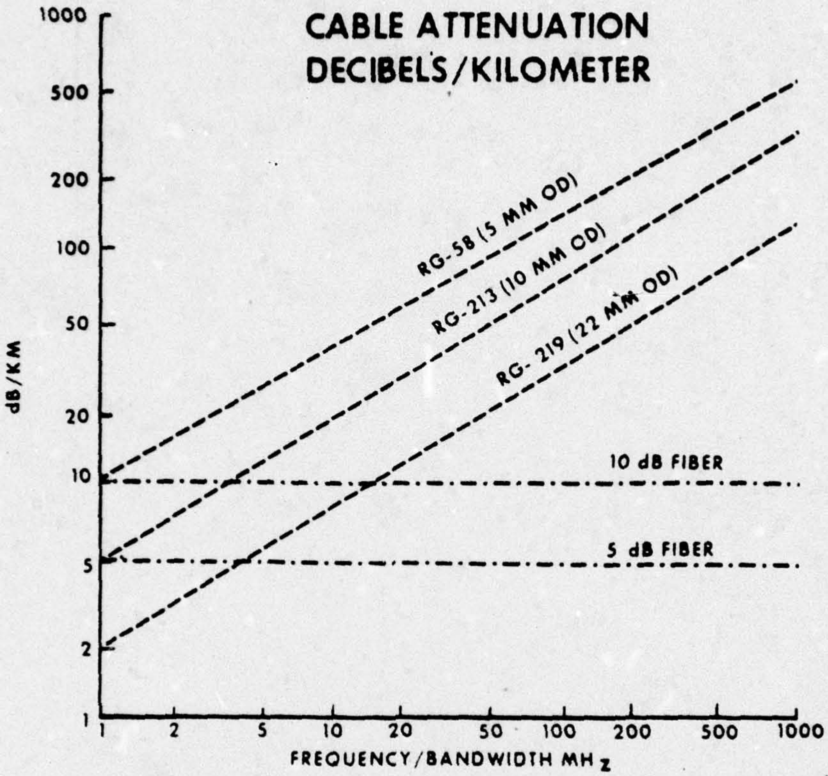


Figure 11. CABLE ATTENUATION (dB/km)

Note that a fiber produced with a 5dB/km attenuation holds essentially that same value regardless of the bandwidth of the modulating signal.

As a practical example, assume a single fiber link is being planned for 500 Mb/s operation, and the selected optical driver (laser) output power and detector (APD) sensitivity provide a circuit loss budget of 65 dB. (This is a realistic figure.) If a high quality 5 dB/km fiber is chosen the link could easily be planned for 8 kilometers between repeaters (40 dB loss). This would still allow a 25 dB margin for splices (about 1 dB each), coupling losses (driver to fiber, and fiber to detector), and a safety factor.

At the same bandwidth, a 10 mm diameter metallic coaxial cable would sustain a loss of approximately 150 dB/km, or a totally unusuable 1,200 dB for an eight kilometer run. The alternative is, of course, closer repeater spacing for the metallic coaxial cable at a significant additional cost.

The fiber optics performance in the above example sounds almost too good to be true. It is in fact true, but there is a catch. As the purity of glass fibers has improved (resulting in lower absorbtion loss), the circuit limiting factor for optical fibers in wideband applications has become group-delay distortion in the form of digital pulse spreading.

The cause of pulse spreading in optical fibers is depicted in figure 12. Three selected light rays from the driver output are shown, all (of course) modulated simultaneously with the same message signal, in this example the leading edge of digital pulse P (see Figure 13).

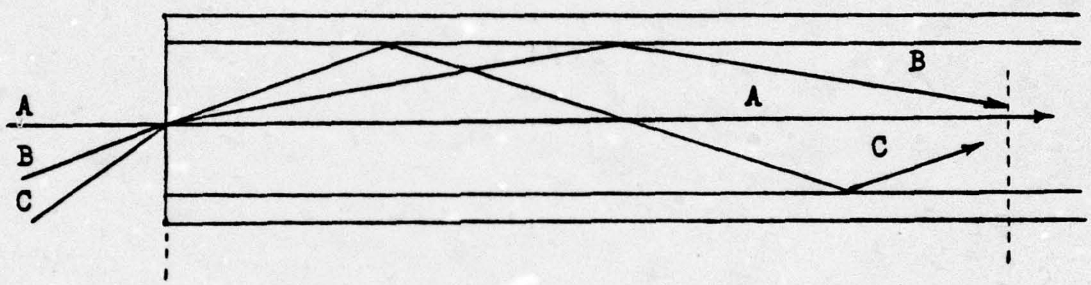


FIGURE 12. PULSE SPREADING IN AN OPTICAL FIBER

All three rays enter the fiber at exactly the same time, t_0, and all three rays are within the maxium angle of acceptance of the fiber. But each ray is obviously, and by definition, traveling in a different mode in the glass, and, because light moves along each ray path or mode at the same velocity, it may readily be seen that the net progress of each ray down the length of the fiber (along the center axis) is not the same. Thus, at an arbitrary time, t_1, (a number of nanoseconds later), the signal has suffered noticeable multimode group-delay spreading, and the once-sharp edge of pulse P (at t_0) is distorted (spread) as shown at time t_1.

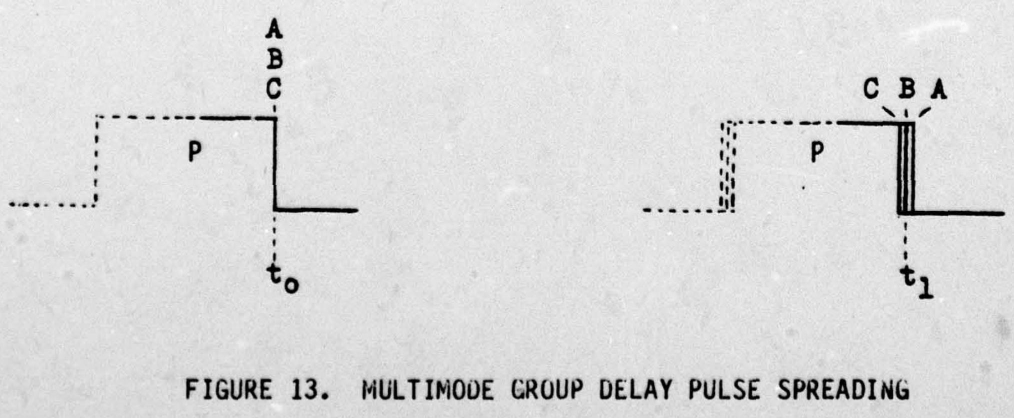


FIGURE 13. MULTIMODE GROUP DELAY PULSE SPREADING

While the velocity of light is high, and the dimensions of the fiber small, this spreading over several kilometers of cable at wide bandwidths (which require narrow, close spaced pulses) does become significant.

2. GRADED-INDEX MULTIMODE FIBER

One approach, and the one most commonly used at present, to combat the multimode delay problem is through the use of graded-index, multimode fibers. The graded index fibers are approximately the same diameter ($\cong$ 100 microns) as step index fibers (multimode), but they have no cladding to provide reflection back into the core area. Instead, the fiber is built up in such a manner that the refractive index of the glass becomes gradually lower as one moves away from the center axis of the fiber and toward the fiber's outer edge.

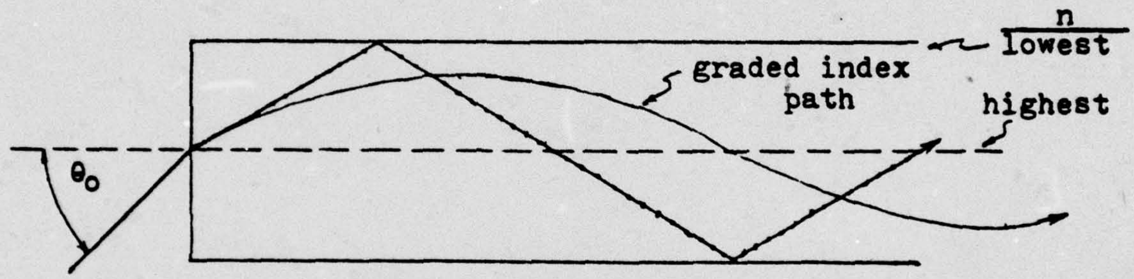


FIGURE 14. LIGHT REFRACTION IN A GRADED INDEX MULTIMODE FIBER

Light rays entering the fiber are not reflected at all, but are gradually (by the continuous small changes in the refractive index) refracted or bent back toward the center of the fiber. The result is a considerable shortening of the maximum (worst case) path length when compared with a reflecting, step-index type of fiber. The step index path is shown by the dotted line in Figure 14. (The path as it would be in a step-index fiber).

With the maximum path (and all those in-between) much closer in actual length to the direct path along the guide axis, the net result is considerably less multimode group-delay spread and a significantly higher digital transmission bandwidth capacity for a given length of cable.

Early production difficulties have been overcome, and the graded-index, multimode fiber is the choice for most wideband applications today.

3. STEP-INDEX SINGLE-MODE FIBER

There is a second, even more effective method of reducing multimode group-delay spread, which, for all practical purposes, eliminates it entirely. The optical fiber is manufactured with the basic step index, core/cladding relationship, but with the core so small in diameter (on the order of 3 to 5 microns) that only light propagated directly along the single mode of the center axis can enter.

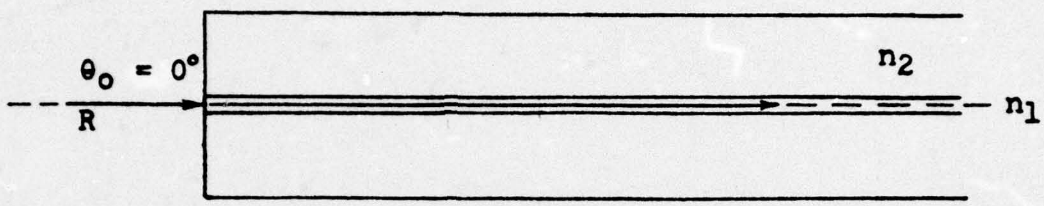


FIGURE 15. LIGHT PROPAGATION IN A STEP-INDEX SINGLE-MODE FIBER

While the use of the single-mode fiber eliminates pulse spreading due to multimode group-delay spread, it uncovers a new group-delay problem which was a lesser contributor before, but which now becomes dominant (dominant at a higher transmission rate - we do not lose the progress made so far). The "new" problem is group-delay distortion caused by material dispersion. Material dispersion is the spreading delay attributable to small internal variations in the index of refraction of the core glass as a function of the wavelength of the light carrier.

Within current technology little can be done to the glass fiber to control this dispersion problem. Thus it is important to reduce the light carrier, at whatever wavelength, to as narrow a bandwidth as possible. In fact, with available narrow spectral width injection lasers ($\cong$ 20 angstroms) and good quality fiber, modulation bandwidths of several gigahertz have been achieved. With the extremely narrow solid-state Nd:YAG laser ($\cong$ 1 angstrom) modulation bandwidths of well over 10 gigahertz are expected. The bandwidth limiting factor will probably be the capability of the external modulator circuitry.

Although the step-index single-mode fiber has considerable bandwidth advantage, it will probably be some time before it is available for routine applications. This is due to the extremely small diameter of the light carrying core. It is not difficult to imagine the problems inherent in attempting to properly align and then splice, particularly in the field, the ends of two glass fibers each only one-fifteenth the size of a human hair.

V. CONSIDERATIONS FOR SYSTEM APPLICATIONS

1. ADVANTAGES OF FIBER OPTICS

In the introduction it was stated that fiber optics provided the solution to numerous problems associated with metallic transmission paths. That statement can best be illustrated by a series of comparisons between fiber and metallic paths for a number of design parameters. This will be followed by two applications examples and a discussion of three areas which may cause problems for certain fiber optics applications.

a. Size. Individual optical fibers are typically only 75 to 125 microns in diameter. This compares with the human hair which averages 70 microns in diameter. Multiple fiber cables can thus average only 5 to 7 millimeters in diameter and even very high capacity configurations with as many as 144 individual fiber paths need run no more than 13 millimeters (one-half inch) in thickness.

To equal that bandwidth carrying capacity with normal metallic coaxial cable would require a cable with 300 times the fiber cable cross-sectional area!

b. Weight. At the low capacity end of the spectrum (a single, narrow-bandwidth path such as a twisted wire pair) much of the weight is in the cabling material, not the conductor. However, even here fiber optics has a fair weight advantage; the twisted wire pair weighs about 35 kg/km, but a two-fiber cable weighs only 25 kg/km. And of course the fiber has a far greater bandwidth capacity available if needed.

At 20 Mb/s the two-fiber cable still weighs 25 kg/km but the required twin coaxial cable for even a reasonable repeater spacing is well over 100 kg/km - a more than four to one advantage in favor of fiber optics.

At composite T-4 rates (roughly a 270 Mb/s total in a multiple coaxial cable) the weight advantage is 240 to 1, for the cable alone. In addition, there are the repeater spacing advantages.

c. Strength. In early fiber optics development, the low physical strength and brittleness of the glass fibers in comparison to copper wire was of some concern. Stronger, more pure fibers and improved cabling techniques have overcome the strength problem.

In addition, glass fibers that strength test at more than 100,000 pounds per square inch have been produced in the laboratory (Bell) by using laser beam heating to reduce surface flaws, and by protective coating the finished fiber with an organic resin compound.

d. Reliability. At present the lifetime reliability objective for components of a full-period communications system is generally on the order of 100,000 hours (about 11 1/2 years) before failure.

Fiber optics is in the unique position of not having been around long enough to actually test any of its components for 11 1/2 years (or even 5 years in most cases), but accelerated tests under excess heat conditions indicate a current status as shown in Table II.

TYPE	HOURS
FIBER	100,000 ++
LASER DRIVER	20,000 ↗
L.E.D. DRIVER	50,000 ↗
PHOTO AVALANCHE DETECTOR	100,000 +
P.I.N. DETECTOR	100,000 +

TABLE II. FIBER OPTICS COMPONENT LIFETIMES, 1978 STATUS

Note: The arrows provide a rough sense of anticipated future progress toward achieving high component lifetimes.

It would appear that the optical drivers require additional development, but in fact initial laboratory tests of newer techniques seem to indicate that injection lasers may now have been developed with a 1 million hour (more than 100 hundred years) lifetime.

Fiber optics has already reached the point where the lifetime limiting factor is usually the associated electronics circuitry.

e. Cost. As in every new technology, the initial costs were quite high for extensive research and development programs, and for production start up. Thus, while the 1970 single fiber cost was about $100 per meter, it has fallen to less than $1 per meter today. A typical 10 fiber cable (10 single fibers plus cabling costs) may now be purchased on the open market for $10 to $12 per meter.

In 1974 a quality injection laser was available for $3,600. That figure, in just 4 years, has dropped to about $100 each in small quantities. Good quality LED's are now selling for less than $20.

Photo avalanche diodes were first produced for fiber optics applications about 7 years ago at around $500 each. That figure is now about $150. The less sensitive p-i-n photo diodes may be acquired for under $50.

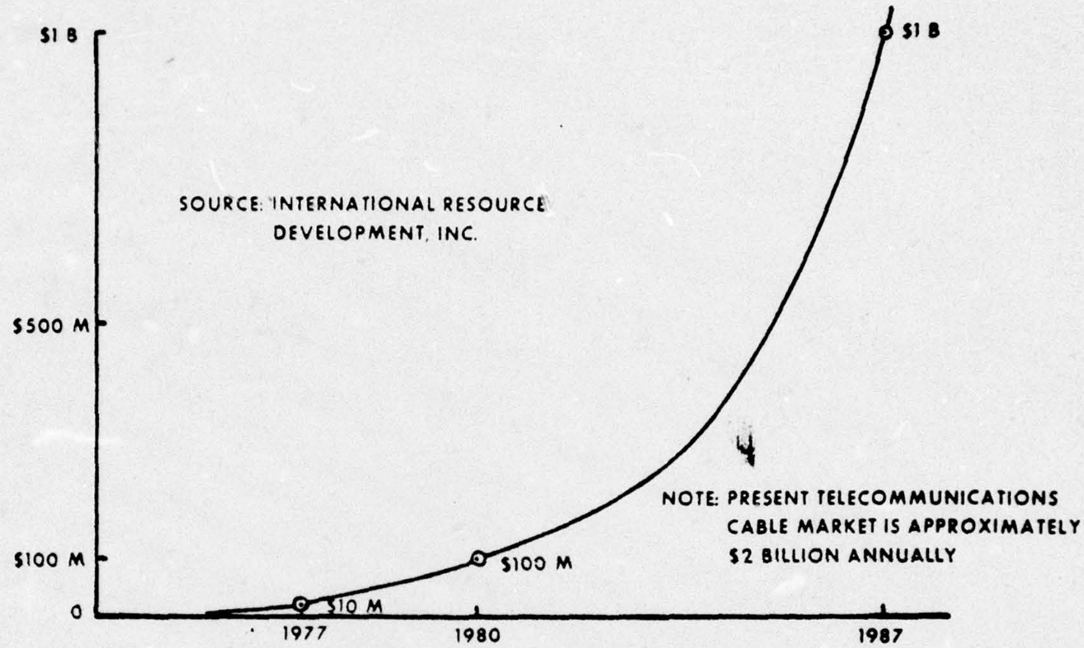


FIGURE 16. FIBER OPTICS - 10-YEAR U.S. MARKET FORECAST

The International Resource Development company, in a recent study report (Figure 16) has indicated that the $10 million 1974 fiber optics commercial market is expected to expand to an incredible $1 billion annually by 1987. By comparison, the total United States telecommunications cable market is now about $2 billion each year. Should these dramatic sales gains materialize as forecast, there is no question that further signifiant reductions in fiber optics hardware prices will occur.

f. Repeater Spacing. Most metallic cables carrying significant bandwidths (20 Mb/s and higher) must be engineered for repeater spacing at 1 to 3 kilometer intervals. In practice, spacings of 1.6 and 1.7 kilometers are quite common.

A fiber optics system carrying the same digital signal can easily sustain a 7 to 8 kilometer spacing, and 10 to 12 kilometers between repeaters for present T-3 rate applications is not unrealistic. This improved repeater spacing factor, generally four or five to one over metallic cable, results in addtional impressive cost and weight savings for fiber optics systems.

As more effective techniques for handling single-mode fibers are developed, along with higher purity fibers and more effective narrowband lasers, the per-circuit cost efficiency of fiber optics will far surpass all other communications transmission means.

I believe it on the conservative side to predict that fiber optics systems in the multigigahertz modulation bandwidth range, with 15 kilometer repeater spacing, will be utilized in the field by 1983.

g. Other Characteristics. Size, weight, and bandwidth capacity considerations alone would make fiber optics a very attractive alternative to metallic cables, but in addition to all this, fiber optics cables are electrically nonconducting. That special property tends to eliminate essentially all of the remaining problems which now plague metallic paths.

Fiber optics systems are immune to line surges, effects of lightning, and signal ground loops. Fibers do not generate electromagnetic interference, nor are they susceptible to such interference from power lines, radio waves, adjacent cable systems, or other sources. The result is a very low noise figure. As nonconductors, optical fibers cannot cause destructive short circuits.

Moisture is a constant problem with metallic cables, particularly in underground (buried) applications, resulting in short circuits, power losses, corrosion, and increased crosstalk. Glass fibers are normally not affected by moisture. The exception occurs when a fiber optics cable is improperly installed with excessive tension placed on the fiber itself (rather than on strength members). Then, the presence of water can slowly expand existing micro cracks on the fiber's outside surface and eventually cause the fiber to break.

Properly constructed and sheathed fibers will not accept stray light incident on their outside cladding and thus crosstalk is non-existent (usually stated as being too low to detect by current methods and standards).

For military applications, the fact that optical fibers do not radiate electromagnetically eliminates any potential TEMPEST problem (see note on page 27), and as nonconductors they neither generate nor carry the destructive electromagnetic pulses (EMP) which are created in metallic conductors by the high fields associated with nuclear weapons detonations.

The softening point of glass generally occurs several hundred degrees Centigrade higher than the melting temperature of copper wire, but thermal expansion mismatch between the core and cladding could cause difficulty at temperatures somewhat lower. However, as a rule, the cabling material for both copper wire and glass fibers would suffer heat damage before the conductor itself. Cabling damage, due to the potential for short circuiting, is of course more of a problem for the metallic cable.

2. APPLICATIONS EXAMPLES

a. Commercial Telephone Metro Area Access Trunking. In this comparison chart of two similar capacity cables (actually, the optical fiber cable provides twice the bandwidth) the cable cost is the same. But the size and weight savings for the fiber cable are immense, and the requirement for more repeaters with the metallic system (almost six times as many) more than compensates for the cost of the optical driver and detector circuitry at each end of the fiber optics system.

	T-4 Metallic Cable	Fiber Optics Cable
TYPE	18 Tube Coaxial	24 Fiber
CAPACITY	9 x 30 Mb/s	12 x 45 Mb/s
DIAMETER	75 mm	10 mm
WEIGHT	12,000 kg/km	50 kg/km
COST	$ 26,000/km	$ 26,000/km
REPEATER SPACING	1.7 km	10 km

b. Miltary Field System. For this example of an 8-Km military field system using a 20 Mb/s signal rate, the planning requirement is real. The small twin-coaxial cable utilized in the tactical environment requires a compact repeater about every 400 meters to sustain the 20 Mb/s rate. The potential replacement system (fiber optics) requires no repeaters, provides a 50 percent cost and weight savings, and will handle twice the modulation bandwidth, if needed, at an equal or better bit error rate (BER).

	Twin Coaxial Cable	Fiber Optics Link
CABLE COST	$ 8,000	$ 8,000
REPEATERS	19	0
REPEATER COST	$ 18,000 (TOTAL)	0
TERMINAL COST	0	$ 4,000 (TOTAL)
SYSTEM WEIGHT	750 kg	300 kg
TOTAL COST	$ 26,000	$ 12,000

3. PROBLEM AREAS

Although fiber optics provides a significant improvement over metallic cable circuits in almost every respect, there are nonetheless a few problem areas. Each, however, is only a problem in certain applications, and each of the following may be solved by present research.

a. Bridging and Conferencing. Because of the optical nature and small size of the fiber optics transmission medium there are obviously difficulties inherent in attempting to distribute the light signal in either collective or individual addressee, multiple terminal networks. Methods of packing several light signals (of slightly different carrier wavelengths) onto a single fiber are being investigated, as well as various means of splitting and/or combining fibers serving individual terminals in the same net. Optical techniques under study include bidirectional couplers using a glass mixing block with internal mirrors; T-access couplers consisting of bent Pyrex rods bonded to a mixing rod; and star distribution couplers. All, however, involve significant insertion loss, and are in general only effective in relatively short distance, fiber bundle type applications.

b. Repeater Power. A problem exists in the provision of electrical power to operate repeaters on long haul fiber optics circuits. In many routine metallic cable applications the repeater power simply rides along on the metallic conductors of the cable, and is tapped off at each repeater. With fiber optics there is no electrical path, so repeater power must be provided by: (1) Adding a metallic pair to the fiber optics cable (which increases weight and size, and more importantly reduces the fiber cable's immunity to electrical effects and phenomena; (2) using internal batteries and/or solar cells, or (3) locating each repeater near a source of commercial electrical power.

Each of these "solutions" can create additional logistics problems, although good systems planning can often avoid much of the impact.

c. Electrical Signaling Path. In certain nonmultiplexed wire line applications, the metallic path of the wire or cable is used to pass an AC ringing signal in addition to the voice message signal. As there is no metallic path in the fiber optics cable such ringing currents must first be converted to a voice frequency tone and then sent as a part of the voice band modulation. Thus there is a requirement for ringing signal converters, generators, and filters, which adds significantly to system costs. But, as previously stated, this problem exists for only a few specific nonmultiplexed wireline type applications.

VI. POTENTIAL EMPLOYMENT IN THE DCS

In addition to the numerous benefits provided to all classes of communications users, the nonsusceptibility of fiber optics to a variety of nuclear phenomena makes this new technology of special interest to the military community.

The size and weight savings are of considerable logistics value for both tactical and strategic employment, and the electrical isolation and nonradiating properties of optical fibers provide solutions for a number of TEMPEST problems. The latter two characteristics coupled with the extremely small size of the fiber and the nature of the signal (light instead of electric) being transmitted also assure a substantial degree of intrinsic physical security. (See note on this page.)

Thus it seems likely that the military communications communities, both tactical and strategic, should and probably will become significant users of fiber optics technology in the near future.

The following specific applications might be prime candidates for fiber optics employment in the DCS:

- Satellite ICF
- Protected Wireline Distribution Systems
- Wideband Tech Control Patch & Test
- DCS Cable Segment Replacement
- Transportable/Recoverable Module Interconnects
- LOS "Down The Hill" Radio/Mux Links
- Computer Processor/Terminal Security

Note: It is emphasized that the security related advantages cited are in the areas of TEMPEST considerations and physical security (such as making it difficult to place a tap on a circuit), rather than in actual message encryption. In the present state-of-the-art there is no absolute message or transmission security capability inherent in Fiber Optics; thus cryptographic equipment is still required for classified traffic and bulk transmission security applications.

VII. SUMMARY AND CONCLUSIONS

Today, in many types of applications, both civil and military, for approximately the same cost as a metallic circuit, a fiber optics system can be installed which will provide the potential for a much greater bandwidth capacity, and;

- Immunity from lightning, EMI, RFI, TEMPEST, EMP, groundloops, and crosstalk.

- Electrical isolation; no spark/fire hazard, destructive short circuits, noise, ringing, or echoes.

- Higher strength, higher temperature tolerance, and resistance to moisture/corrosion.

- Smaller size, lighter weight, and lower power consumption.

The only significant disadvantage is the requirement for the two additional components (optical driver and optical detector) and their associated circuitry, and, in certain situations, the requirements for remote repeater power.

The potential communications applications for Fiber Optics are limitless, and, looking even a bit further ahead, this new technology may ultimately make practical the provision of high quality digital CATV, as well as various query/response and two-way computer interfaces, in every home.

It would appear that nothing else in favor of fiber optics need be said, but there is nevertheless one final plus factor. As communications bandwidth requirements continue to increase, metallic cable production takes an ever larger bite of one of our country's most critical materials - pure copper.

On the other hand, to make an optical fiber,

"Take one large pile of sand. . ."

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